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TO THE FAR SIDE OF THE SUN USING VENUS GRAVITY ASSIST*

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ABSTRACT

The recent NASA initiative to investigate our sun in depth, called "Living with a Star" (LWS), includes consideration of several possible deep space missions one of which is placing a satellite on the far side of the sun so that, together with Earth observation, the full evolution of solar phenomena may be observed as the sun rotates. Unfortunately, in using a direct approach, celestial mechanics does not permit this to be done easily and in a timely manner. Here, the direct approach for satellite placement will be shown to be costly compared with the use of Venus gravity assist. Also, since the satellite will be sent to a specific location in space, and not to a planet, it is necessary to develop software modifications to specifically address this problem.

In this paper, the application will be for the insertion of a Far Side Sentinel (FSS) satellite in the year 2009 into the third quadrant (180 to 270 degrees ahead of Earth) using a double Venus gravity assist. Options for other possible missions, including a distributed set of solar observers will be briefly analyzed.

INTRODUCTION

A world wide chain of ground stations called the Global Oscillation Network Group (GONG) have gathered evidence that release of stress in solar magnetic fields may be driving the 11-year cycle of solar eruptions. This has led NASA to propose a more intensive study of the sun using deep space observation satellites.

Several projects related to NASA's LWS theme are now being considered, one of which is the Far Side Sentinel (FSS). This would be a solar far side observer whose purpose would be to probe the sun's 3-D structure, both magnetic fields and mass flow, from deep within the surface to the outflowing corona. For this, it would be necessary to follow the evolution of active regions, taking full disk magnetic and velocity field observations. Mission requirements include a 2-year on-station observation time, plus a possible 3-year extension.

DIRECT TRANSFER MODES

Consider the types of solar orbits which would be suitable for observing the sun, such as for the FSS. The simplest would be one which is in a 1 AU circular orbit, like the Earth, but positioned a fixed number of degrees ahead or behind the Earth. It's orbital period would be that of the Earth, or 365.25 days. To achieve this orbit, the transfer from Earth would be similar to a rendezvous with a hypothetical asteroid located, say, on the back side of the sun.

To reach this position, a spacecraft would have to be launched from Earth such that it would either lead the Earth by sending it inward towards Venus, or lag the Earth by sending it outward towards Mars. Then, when it reached the desired angular position relative to Earth, and returned to it's perihelion (or aphelion) of 1 AU, it would perform a maneuver to "rendezvous" and remain stationary relative to the Earth-sun line.

The cost in terms of delta-v and the time of transfer is given in Tables 1 and 2, for inward and outward launches. Also, both modes are depicted in Figure 1a, in the usual heliocentric inertial system.

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It is more informative, however, to present the trajectory transfers in a rotating system, with the Earth-sun line fixed, say, along the y-axis. Figure 1b presents the same trajectories as Figure 1a, but in this rotating system.

In the tables below, a flight time of 1.5, 2.5, and 3.5 years implies that the Earth at these times will be located directly opposite from its initial position at launch. Thus if the launch is in January, its position will be on the other side of the sun in July.

On the other hand, the station, if it is to enter a 1 AU circular orbit, must make integral revolutions about the sun to return to its initial starting point of 1 AU to "rendezvous" with its desired position. (The delta-v required for this is given in the tables.) This implies that, in this direct mode, the flight time controls Earth's final position relative to its launch position, which is the station's final position.

Table 1. Inwards Towards Venus
To the Far Side of the Sun (180°)

Flight Time,yr	1.5	2.5	3.5
S/C Solar Revs	2.0	3.0	4.0
Energy, C3	10.71	3.83	1.95
Perihelion , AU	0.668	0.788	0.846
Delta-V(km/s)	3.27	1.96	1.40

Table 2. Outwards Towards Mars
To the Far Side of the Sun (180°)

Flight Time,yr	1.5	2.5	3.5
S/C Solar Revs	1.0	2.0	3.0
Energy, C3	10.83	3.85	1.95
Aphelion , AU	1.637	1.337	1.233
Delta-V(km/s)	3.29	1.96	1.40

It can be noted in the tables that the results of both transfer modes are very similar and that the cost in transfer time and delta-v are high. The most reasonable would be the 2.5 year transfer time and a delta-v of about 2 km/s. The C3 value is low, only about 4 km^2/s^2. Fortunately, inserting Venus flybys can reduce the flight times to 1 year, and eliminate the orbit insertion delta-v. The final station orbit, however, would be elliptical and not circular.

SINGLE VENUS GRAVITY ASSIST

Compared with direct to the far side of the sun, Venus gravity assist can avoid both long flight times and large delta-v's for the station insertion into a 1-year orbit. However, the condition which is compromised is the 1 AU circular orbit achieved with the direct mode. Instead, the 1-year final orbit will have a perihelion roughly at Venus' orbit, and an aphelion at 1.28 AU. This may be a small price to pay to avoid a 2.5 year flight time and a 2.0 km/s insertion velocity requirement.

A launch to Venus requires about 5 months for a simple Hohmann transfer. Venus perihelion is 0.72 AU, which is about half way between the 1.5 and 2.5 year flight time shown in Table 1. This in fact is ideal, since now, in a two-year period, the Hohmann transfer orbit will make 2.5 revolutions (in 5x5 months) so that the station will end up at Venus, and the Earth will return to its launch location. The launch date, of course, must take the extra 2 revolutions of the transfer orbit into account in computing the Earth-Venus transfer. A typical transfer of this sort, in the rotating system, is shown in Figure 2.

In this figure, the Earth is fixed at the origin, and the sun at 1.0 on the Y-axis. The orbit of the transfer to Venus has an aphelion of 1 AU, and a preihelion of 0.72 AU. The spacecraft motion is ahead of the Earth and completes one revolution when it returns to 1 AU at about 75° from Earth. A second revolution takes it to about 150°. Another half revolution takes it to an encounter with Venus where an unpowered flyby raises aphelion to 1.28 AU, or to an orbit with a period of 1 year. In the rotating system, this orbit is stationary with respect to the Earth-sun line, with its motion in the sky appearing to trace out a large loop from 23° east to 14° west relative to the sun. Figure 2 traces out this loop for one year.

GRAVITY ASSIST COMPUTATION

As will be seen later, specifying terminal orbits for other than a 1-year period will be useful for the design of the FSS. For this reason, to avoid a difficult iterative search for the flyby conditions with the standard programs available, a modification was made to an existing interplanetary program to allow automatic computation of flyby conditions for a given post-flyby heliocentric period.

Using the point conic model, a planetary encounter is approximated by translating the approach spacecraft heliocentric velocity vector into a Venus centered velocity-at-infinity vector ($V_{\infty 1}$) by subtracting off the Venus velocity vector at encounter, or

$$V_{\infty 1} = V_{h1} - V_v$$

Similarly, the outbound velocity-at-infinity, which would have the same magnitude as the inbound would then be used in reverse to get the outbound heliocentric velocity, or

$$V_H = V_{\infty 2} + V_v$$

The problem then is, given the inbound velocity-at-infinity and the desired heliocentric outbound period (P_e), find the Venus flyby conditions.

The outbound major axis of the orbit may be computed from

$$A_e = [\mu_s(P_e/2\pi)^2]^{1/3}$$

where, μ_s is the sun's gravitational constant.

Then, given the Venus distance from the sun, the outbound heliocentric velocity must be,

$$V_H = \mathrm{sqrt}[\mu_s(2/R_V - 1/A_e)]$$

which is the magnitude of the vector above.

At this point, it is necessary to refer to Figure 3 since there are multiple solutions depending on the inclination of the Venus flyby. In this figure, the Venus velocity vector is known, but only the magnitudes of V_H and $V_{\infty 2}$ are known.

Since three sides of the vector diagram are known, the set of solutions consist of this vector triangle rotated about the Venus velocity vector. The vector $V_{\infty 2}$ forms a cone, and specifying a cone angle pins down the vector directions of $V_{\infty 2}$ and V_H.

The next step is to use the inbound and outbound V_∞ vectors to compute the specific Venus flyby inclination and altitude. The details will not be given here, but the two vectors give the inclination of the hyperbolic flyby, and the angle between them gives the Venus flyby altitude. The altitude can be examined to see if the flyby passes beneath the Venus surface. These solutions are obviously rejected.

Also, a given cone angle will specify a given outbound heliocentric velocity vector, which together with the Venus position vector will determine the heliocentric orbit elements. Again, the characteristics of the orbit can be examined to see if some constraint is violated, such as passing too close to the sun for communication with Earth.

It should be noted in the vector triangle of Figure 3, that no solution will be available if the magnitude of V_H is greater than the sum of V_v and $V_{\infty 2}$. Since the Venus orbital velocity is fixed, this implies that $V_{\infty 1}$, which has the same magnitude as $V_{\infty 2}$, must have a minimum value. That is, the approach $V_{\infty 1}$ must be larger than a certain value which may restrict minimum energy transfers to Venus. Fortunately, suitable transfers can usually be found close to the minimum for a 1-year orbit, with a large enough $V_{\infty 1}$.

DOUBLE VENUS GRAVITY ASSIST

Instead of doing two and one-half revolutions before arriving at Venus for the gravity assist into a 1-year orbit, it is possible to insert one intermediate gravity assist to decrease the heliocentric period and advance faster ahead of the Earth. Specifically, a direct transfer to Venus could be flown for a gravity assist into a Venus type circular orbit. This would require a Venus flyby over the north or south pole so that the outbound $V_{\infty 2}$ would be perpendicular to V_v.

The result would be an inclined Venus type orbit having a period, like Venus of 225 days, or about 7 months. In this time, the spacecraft would advance about 140° ahead of Earth. This, together with the 35° advance during the Earth-Venus transfer would place the spacecraft almost directly on the sun's far side, where a second Venus encounter would result in a 1-year orbit about the sun.

This transfer, the two flybys, and the 1-year orbit are shown in Figure 4a for the type 1 trajectory. The longer type 2 is shown in Figure 4b. The launch date chosen is one which would be suitable for the FSS. Also, the Earth-sky view, the spacecraft radial distance from Earth, and the spacecraft-sun radial velocity are given in Figures 5a and 5b.

For both type trajectories, the Venus arrival date for the first flyby is chosen so that the approach velocity $V_{\infty 1}$ (which is the same at the second flyby) is large enough to enter the 1-year orbit (see the Gravity Assist Computation section above).

THE FAR SIDE SENTINEL

The fact that there is a choice of cone angle for a given desired heliocentric period, as shown in Figure 3, allows other constraints to be satisfied. For example, a requirement may be to enter a 1-year orbit and have a solar occultation, as seen from Earth, once or twice a year, for precise relativity measurements of the bending of light. Then, a particular cone angle may result in this desired orbit.

For the FSS, the opposite is the case. That is, to avoid close passages of the sun which would cause communication interference with Earth. In this case, a different cone angle would be chosen which would attempt to avoid close approaches to the sun.

Another desirable requirement for the FSS spacecraft is for it to drift in the 3rd quadrant over a period of about 3 years. This can be accomplished by decreasing the period of the heliocentric orbit entered after the 2nd Venus flyby, so that during each revolution, it will move forward faster than the Earth.

It was found, through trials, that a period of 345 days will give the desired results. Figures 6a and 6b present trajectory plots for these orbits for the types 1 and 2 transfers to Venus. The type 2 transfer was found to be most favorable if a later Venus arrival date was used, which caused the first orbit to be further into the 3rd quadrant avoiding communication interference with the sun.

ANOTHER LWS APPLICATION

Use of a double Venus gravity assist may also be useful for inserting a set of Inner Heliospheric Sentinels (IHS), which is a mission currently being examined for the LWS initiative. Here, several satellites would be placed in orbits interior to Earth's orbit to view the sun on all sides simultaneously.

In this case, the Earth location would not be major consideration, so that orbits less than one year could be chosen. The Venus period in this case, which is 225 days, would play a dominant role.

As a simple example, consider that 4 satellites are launched to Venus on the type 1 trajectory shown in Figure 6a. At the first Venus encounter, one of them can be aimed for a close flyby to place it in a 180 day heliocentric orbit. It's perihelion will be about 0.5 AU. The other three spacecraft have flybys which place them into a Venus type orbit, as shown in Figure 6a, which will encounter Venus again 225 days later.

The spacecraft placed into the 180 day orbit will perform one complete revolution, and then travel another 90° in the 225 days it takes for the other spacecraft to encounter Venus, and so it will lead Venus by 90°. At Venus, a second spacecraft will perform a flyby to enter a 180 day heliocentric orbit, and this one will be positioned 90° behind the first.

This process will be repeated for the 2 remaining spacecraft, resulting in the placement of 4 satellites in exactly the same orbit (since Venus returns to the same inertial location for each flyby), but displaced by 45 days in their location on the orbit.

The time from the first satellite insertion to the fourth will be three Venus revolutions or less than 2 years. Other scenarios for placement of these 4, or more, satellites could probably be devised for which Venus gravity assist would be beneficial.

SUMMARY

It has been shown that Venus gravity assist can play a major role in the placement of satellites in the inner solar system. Here, for the FSS, a double Venus gravity assist can position a satellite on the far side of the sun in a year, and for no deterministic delta-v if an elliptic orbit is acceptable.

It is also shown that if only the period of the post-Venus flyby is specified, there will be multiple solutions, allowing another condition to be imposed on the trajectory. A computational process is presented by which the set of these possible solutions may be found.

Finally, a general method of placing a network of small satellites evenly spaced around the sun using Venus gravity assist is discussed briefly, where these satellites can be flown to Venus in a single launch period, and perhaps on a single launch vehicle.

In all of these cases, a point conic model of trajectories at Earth and Venus is assumed, which is sufficient to determine initial configurations, but these results should be followed up with more precised integrated computations.

ACKNOWLEDGEMENTS

Funding for this study was provided by the LWS project with direction from R. A. Wallace and J. A. Ayon. The software used, except for modifications, was developed during mission design studies performed for Discovery and SMEX proposals. Finally, credit has to go to Walker Vaning for suggesting a double Venus swingby in 1996, after I had done two studies using single swingbys to reach the far side of the sun.

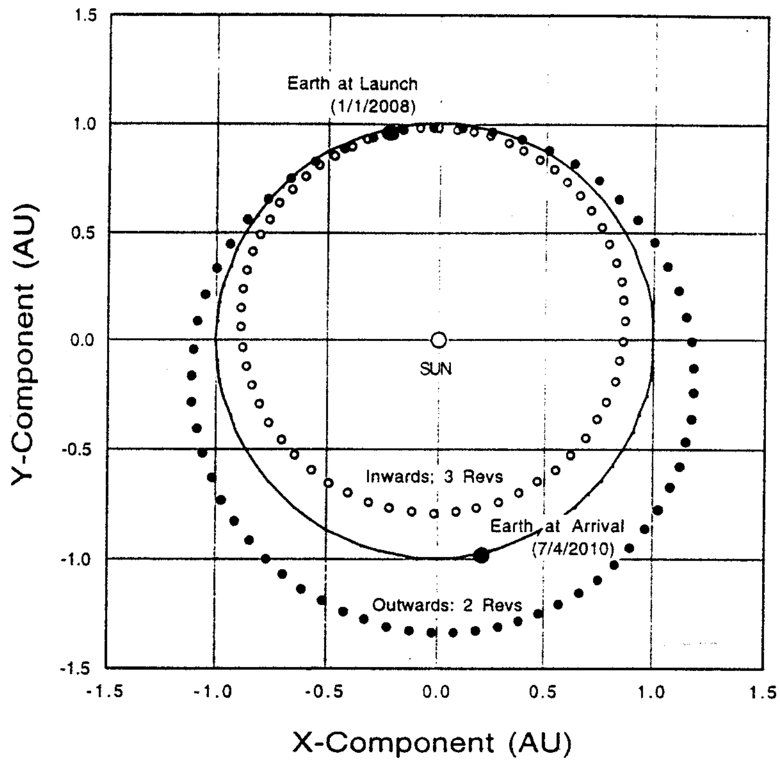

Figure 1a. Direct Transfer to the Sun's Far Side. Inertial Plot

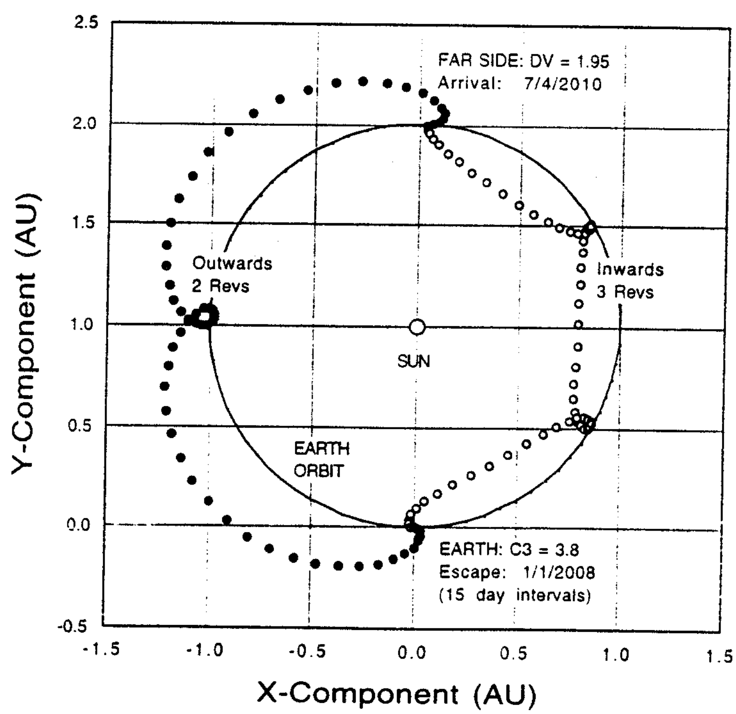

Figure 1b. Direct Transfer to the Sun's Far Side. Earth-Sun Fixed Plot

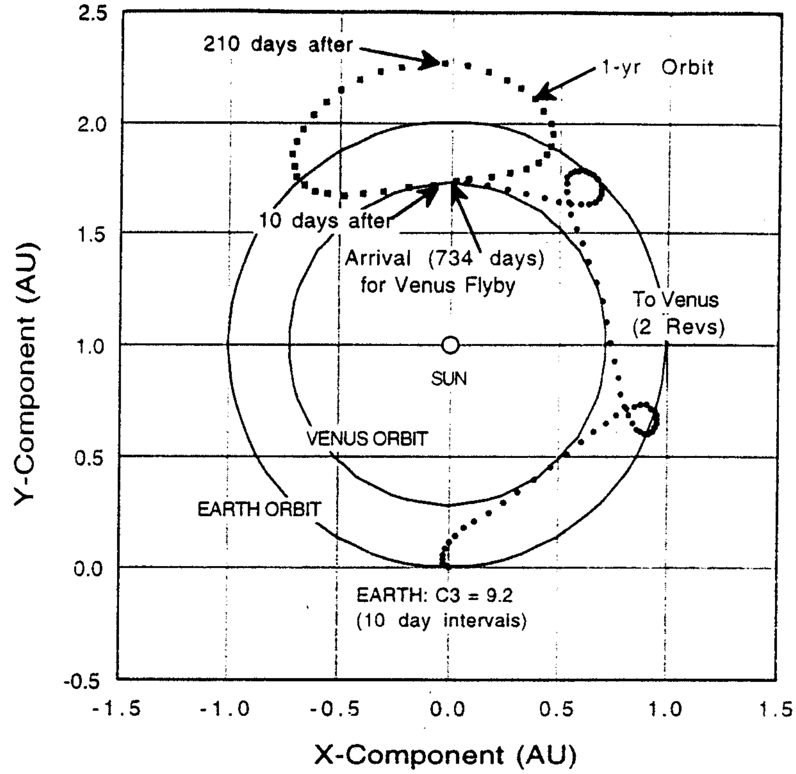

Figure 2. A 2.5 Revolution Transfer to a Venus Flyby and into a Far Side One-Year Orbit

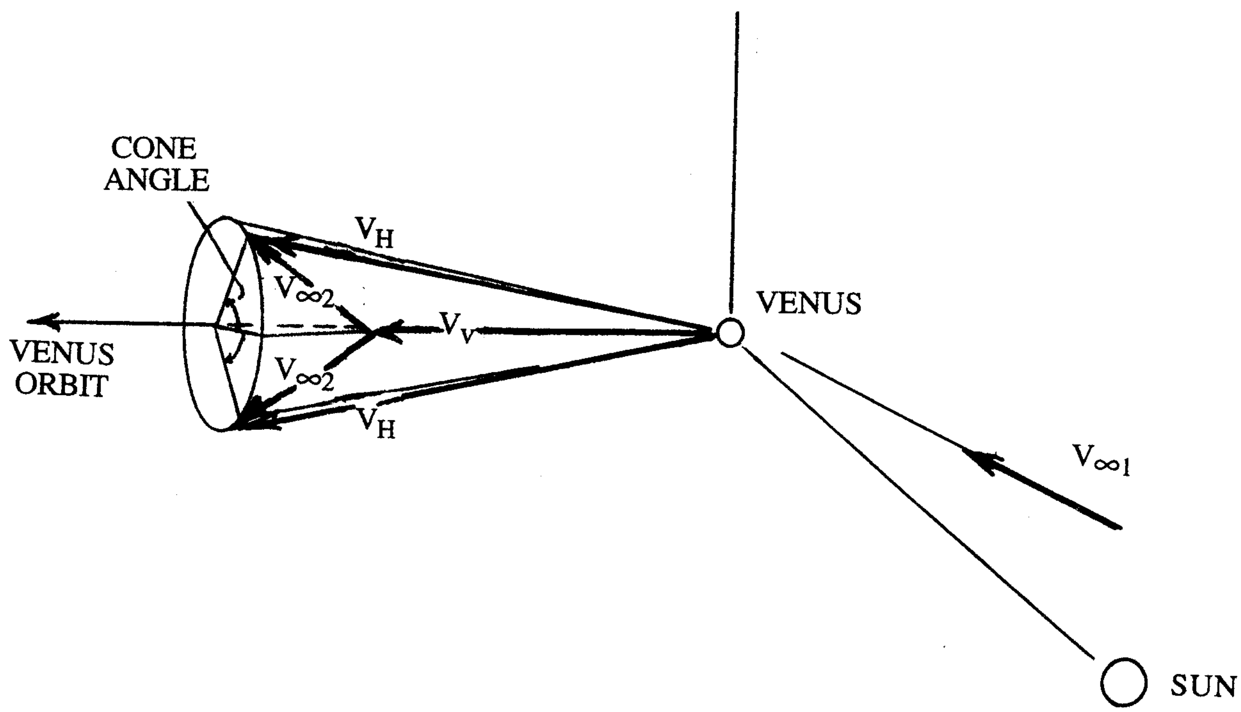

Figure 3. Venus Departure Velocity Cone for a Fixed Heliocentric Orbit Period

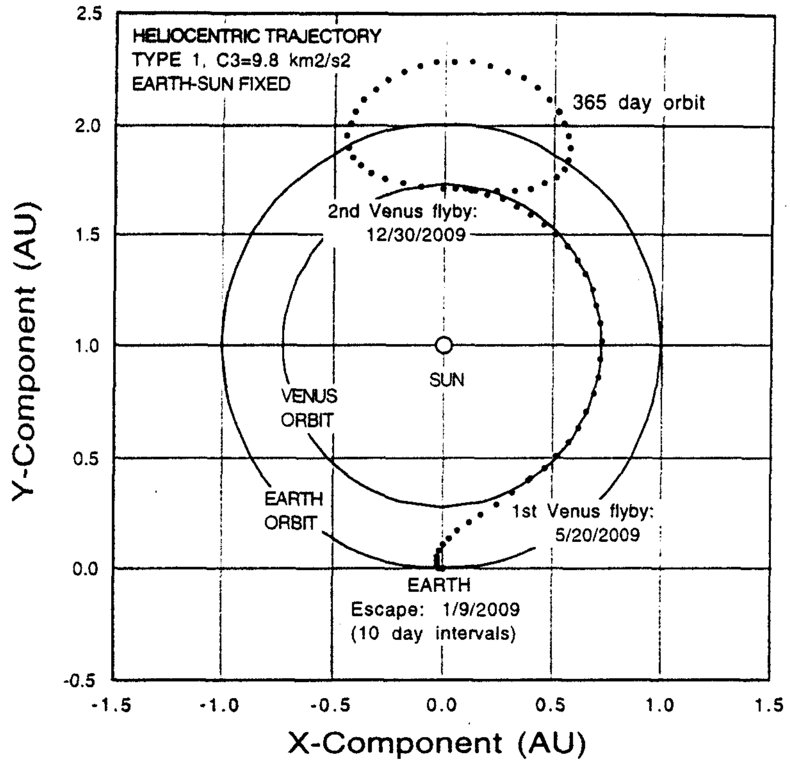

Figure 4a. A Double Venus Flyby into a Far Side One-Year Orbit (Type 1 Transfer)

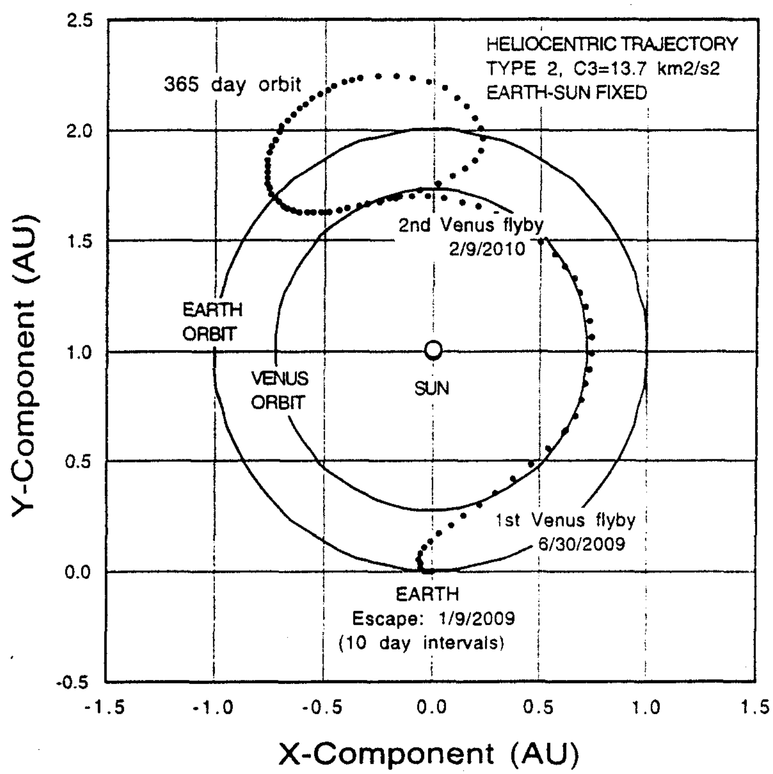

Figure 4b. A Double Venus Flyby into a Far Side One-Year Orbit (Type 2 Transfer)

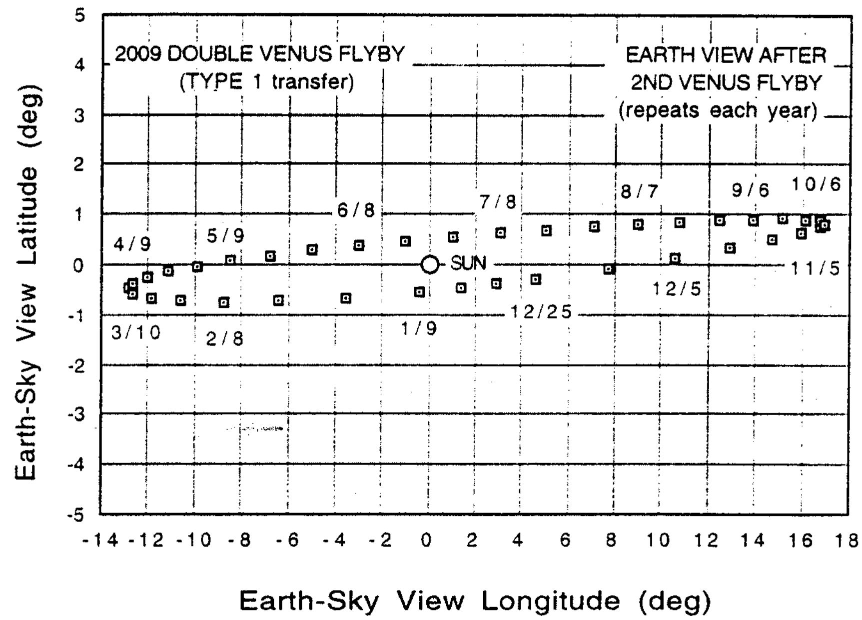

Figure 5a. Earth View of the Far Side 1-Year Orbit Period Spacecraft

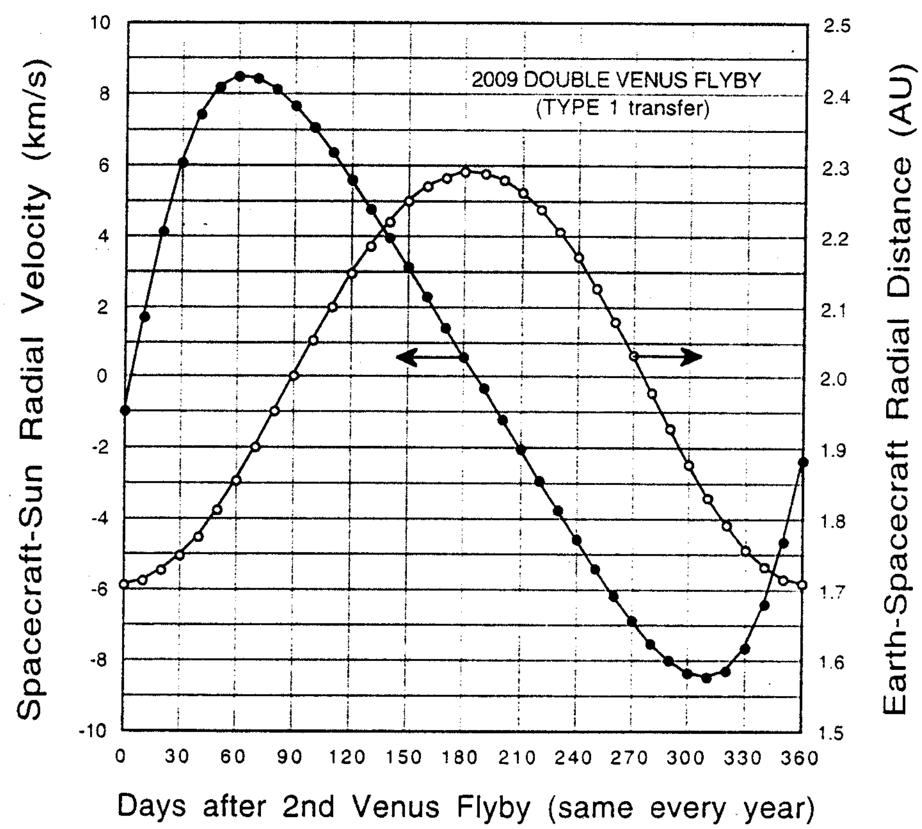

Figure 5b. Earth Distance and Solar Radial Velocity of the 1-Year Orbit Period Spacecraft

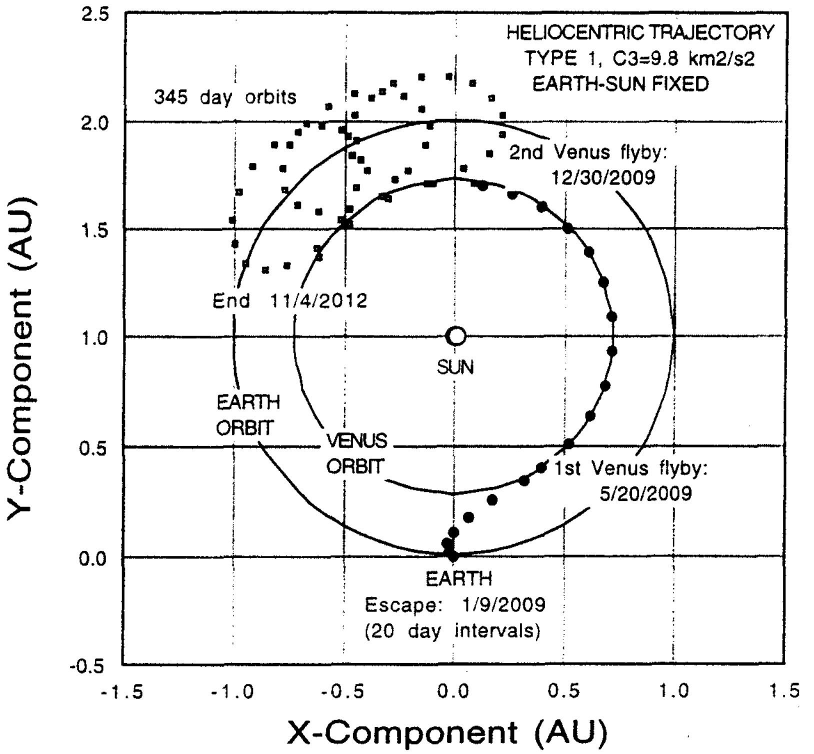

Figure 6a. A Double Venus Flyby into a Sentinel 345 day Orbit (Type 1 Transfer)

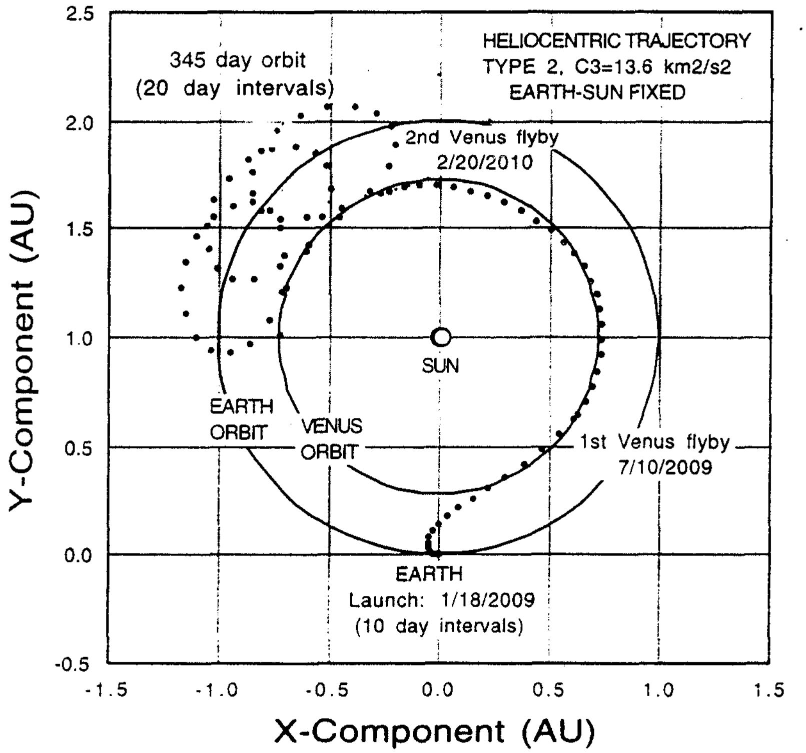

Figure 6b. A Double Venus Flyby into a Sentinel 345 day Orbit (Type 2 Transfer)